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Isham, Brett C.

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Interamerican University of Puerto Rico
Bayamón Campus
500 Dr. John Will Harris Road
Bayamon, PR 00957-6257, USA

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Air Force Office of Scientific Research
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14. ABSTRACT

During Fall 2005 and Fall 2006 experiments were carried out at EISCAT in Norway aimed at advancing related science questions while improving the technical capabilities of ground-based radar and radio remote sensing systems. Significant progress was made between these campaigns in technical equipment capabilities and groundwork was laid for future advances. Related collaborations were initiated in advance of the 2006 campaign to assist in 2006 and future experiments. Radio and computer equipment was purchased for use during the 2006 campaign and beyond. Wideband plasma line channels and remote observations in Sweden and Finland were implemented on the EISCAT Tromsø radar, and an additional radio instrument was fielded in the 2006 campaign. Results were presented by the PI at two international meetings (one invited). The grant helped maintian momentum in the hiring of a new research faculty member and it is expected that there will be a new hire in August 2007. Four students are currently involved in work related to the project.

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Ionospheric turbulence, incoherent scatter radar, stimulated electromagnetic emission, radio propagation, radio interferometry, digital radio receiver, direction angle dependence, ionospheric heating experiments, active experiments in space, HF radiowave pumping experiments.

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Final Report (28 February 2007)

Aspect angle dependence of pump-induced turbulence in the ionosphere (short-term support)

Contract number FA9550-06-1-0308
15 Apr 2006 to 30 Nov 2006 plus 210-day pre-agreement cost period

Dr. Brett Isham (PI), Interamerican University of Puerto Rico, Bayamón, Puerto Rico, USA

Abstract (100 to 200 word abstract summarizing technical progress during the reporting period (identical to item 14 of Standard Form 298)):

During Fall 2005 and Fall 2006 experiments were carried out at EISCAT in Norway aimed at advancing related science questions while improving the technical capabilities of ground-based radar and radio remote sensing systems. Significant progress was made between these campaigns in technical equipment capabilities and groundwork was laid for future advances. Related collaborations were initiated in advance of the 2006 campaign to assist in 2006 and future experiments. Radio and computer equipment was purchased for use during the 2006 campaign and beyond. Wideband plasma line channels and remote observations in Sweden and Finland were implemented on the EISCAT Tromsø radar, and an additional radio instrument was fielded in the 2006 campaign. Results were presented by the PI at two international meetings (one invited). The grant helped maintian momentum in the hiring of a new research faculty member and it is expected that there will be a new hire in August 2007. Four students are currently involved in work related to the project.

Note: In the following, "the grant", "the recently-completed grant", etc., refer to the grant which is the subject of this final report (grant number FA9550-06-1-0308, PI Dr. Brett Isham).

The radio technique used to determine the direction to the radiowave-pumped stimulated electromagnetic/radio emissions (SEE) is described in detail in

Isham, B., T. Hagfors, B. Khudukon, R. Yu. Yurik, E. D. Tereshchenko, M. T. Rietveld, V. Belyey, M. Grill, C. La Hoz, A. Brekke, and C. Heinselman (2005), An interferometer experiment to explore the aspect angle dependence of stimulated electromagnetic emission spectra, *Ann. Geophysicae*, *23*, 55–74, SRef-ID:1432-0576/ag/2005-23-55.

which was published about the time that the recently-completed grant was proposed. Further details of the technique and results obtained during the period of the grant are contained in

Tereshchenko, E. D., R. Yu. Yurik, B. Z. Khudukon, M. T. Rietveld, B. Isham, V. Belyey, A. Brekke, T. Hagfors, and M. Grill (2006), Directional features of the downshifted peak observed in HF-induced stimulated electromagnetic emission spectra obtained using an interferometer, *Ann. Geophysicae*, 24, 1819–1827.

which was published with support from the grant. Additional details of the radio direction-finding algorithm are given in the appendix at the end of this document.

Related publications discussing the properties of stimulated radio emissions and to which the PI contributed and which were published during the grant period are

Ashrafi, M., M. Kosch, K. Kaila, and B. Isham (2007), Spatio-temporal evolution of radio wave pump-induced ionospheric phenomena near the fourth electron gyro-harmonic, *J. Geophys. Res.*, accepted for publication.

and

Gustavsson, B., T. Sergienko, M. J. Kosch, M. T. Rietveld, Å. Steen, B. U. E. Brändström, T. B. Leyser, B. Isham, P. Gallop, T. Aso, M. Ejiri, T. Grydeland, C. La Hoz, K. Kaila, J. Jussila, and H. Holma (2005), The electron energy distribution during HF pumping — A picture painted with all colors, *Ann. Geophysicae*, 23, 1747-1754, SRef-ID:1432-0576/ag/2005-23-1747.

The following publication describes radio observations of scintillation phenomena, and to which the PI contributed and which was published during the period of the grant. The radio technology and the phenomena being studied are both related to the stimulated radio emission phenomena.

Tereshchenko, E. D., B. Z. Khudukon, M. T. Rietveld, B. Isham, T. Hagfors, and A. Brekke (2006), The relationship between small-scale and large-scale ionospheric electron density irregularities generated by powerful HF electromagnetic waves at high latitudes, *Ann. Geophysicae*, 24, 2901–2909.

In all, three publications related to the goals of the grant were published with the PI as co-author during the period of the grant.

In addition, during the period of this grant a project to study, develop, acquire, and use new digital receiving systems was carried out, and three proposals for new digital radio receivers with much wider bandwidth, adjustable to perhaps 10 MHz, to cover ionospheric plasma frequencies, or even to 20 or 30 MHz, to cover harmonics of the plasma frequencies, were developed and submitted (the grant PI is also as PI on the proposals). The new receiver could have a dozen or more coherent raw data channels, sufficient to compare data on many baselines and to compute sky images of stimulated radio emissions as a function of time. One proposal, submitted to DoD EPSCoR, received highest and second-highest evaluations from the two referees but was declined by the local EPSCoR office; the PI and co-I are planning to resubmit directly at the Federal level. The results of the other two proposal competitions (DURIP and NSF MRI) are not yet known.

Other goals of the proposal which were pursued during the grant period include implementation of wideband radar plasma line observations and simultaneous remote observations at the EISCAT ISR receiving sites in Sweden and Finland. The grant provided momentum in the hiring of a new research faculty member and it is expected that someone will be hired in August 2007. Furthermore, four students are currently involved in work related to the project.

The grant provided direct support for the following:

(1) Travel for observing campaign in Norway (September/October 2005) ($1636.04 (partial expenses))

EISCAT Tromsø has the unique capability of operating two ISR systems, one of which has three widely-spaced receivers, and is therefore able to provide a geometrical view of k space unavailable from any other system. One of these radars has been however under threat of mothballing at the end of 2006. The October 2005 observational campaign at EISCAT Tromsø was critical both to ensure that key project goals requiring the use of the EISCAT system are achieved in the event that important instruments are retired from service. Campaigns also serve to maintain momentum and progress in the project. In addition, the PI's Russian, Norwegian, German, and UK collaborators rely on his contribution to the radar and radio projects and to joint campaigns.

(2) Purchase of recording supplies and radio equipment for observing campaign in Norway (October/November 2006) ($3,541.34)

The raw sample data recording systems used in this project require large amounts of disk space. Due to this support I was able to contribute several terabytes to data recording during the observations.

(3) Purchase of computer and accessories (August 2006) ($4827.80)

The project computer used by Dr. Isham was replaced. The old machine was seven years old and had suffered suffered two disk crashes. This machine is used for all programming, data analysis, presentation, and publication work related to the project.

(4) Travel for project development and presentation of results (May-August 2006) ($8649.80)

See 4a and 4b immediately below.

(4a) Travel for digital radio project development, equipment preparation, data analysis, data modeling, and related collaboration (May-August 2006)

The work performed on these visits made possible the beginning of new radio equipment development, some of which was used in an observational campaign in Norway in October/November 2006. The work is continuing both in the areas of equipment development and use and in data analysis and modeling.

— Dartmouth College (Dr. Jim LaBelle), May 2006 and June 2006
— Uppsala University LOIS project (Dr. Bo Thidé), June 2006
— Virginia Tech (Dr. Wayne Scales), July 2006
— University of Washington (Dr. John Sahr), August 2006

In addition a visit to Haystack Observatory (Dr. Frank Lind) was made in November 2005 with the same goals but which was not supported by the grant.

(4b) Travel for presentation of results (May-June 2006)

Results were reported by the PI at two international conferences.

— Dynamical Processes in Space Plasmas, Ben-Gurion University, Israel, May 2006
— Auroral Structures and Kinetics (ASK), Royal Institute of Technology (KTH), Stockholm, Sweden, June 2006 (invited)

Total budget $18,680.00, total expenses $18664.98.

APPENDIX: Interferometric Radio Direction-Finding Algorithm

The direction-finding algorithm for phase-coherent radio emission data recorded on three antennas (two antenna pairs) is described here.

Consider three receiving points (antennas) located at coordinates

$$\vec{r}_m = \vec{i} \cdot x_m + \vec{j} \cdot y_m + \vec{k} \cdot z_m \tag{1}$$

Here m is the antenna index ($m = 0, 1, 2$) and vectors $\vec{i}$, $\vec{j}$ and $\vec{k}$ are unit vectors along the x, y, and z axes, oriented in the west-to-east, south-to-north, and vertical directions, respectively. For simplicity, assume that $z_m = 0$ for all m, i.e. that the antennas are situated in a plane lying perpendicular to the zenith direction. In the case of an indicent plane wave with wave vector $\vec{k}$ ($|\vec{k}| = k = 2\pi/\lambda$ where λ is the wavelength) the phases in antennas 1 and 2 relative to antenna 0 are

$$\Delta\Phi_1 = \vec{k} \cdot \Delta\vec{r}_1 = k_x(x_1 - x_0) + k_y(y_1 - y_0) = k_x X_1 + k_y Y_1 \tag{2}$$

$$\Delta\Phi_2 = \vec{k} \cdot \Delta\vec{r}_2 = k_x(x_2 - x_0) + k_y(y_2 - y_0) = k_x X_2 + k_y Y_2 \tag{3}$$

These equations may be solved to obtain

$$k_x = \frac{\Delta\Phi_1 Y_2 - \Delta\Phi_2 X_1}{X_1 Y_2 - X_2 Y_1} \tag{4}$$

$$k_y = \frac{\Delta\Phi_2 X_1 - \Delta\Phi_1 Y_2}{X_1 Y_2 - X_2 Y_1} \tag{5}$$

$$k_z = -\sqrt{k^2 - k_x^2 - k_y^2} \tag{6}$$

and the corresponding angles of arrival (elevation ε and azimuth α) are

$$\varepsilon = \arcsin\left(\frac{-k_z}{k}\right) \tag{7}$$

$$\alpha = \arctan\left(\frac{-k_y}{-k_x}\right) \tag{8}$$

The values of phase difference are 2π-ambiguous, i.e.

$$\Delta\Phi_1 = \Delta\phi_1 + 2\pi n_1 \tag{9}$$

$$\Delta\Phi_2 = \Delta\phi_2 + 2\pi n_2 \tag{10}$$

$$n_1, n_2 = \cdots -2, -1, 0, 1, 2, \cdots \tag{11}$$

However, with appropriate choice of antenna spacing the unwanted repetition in phase will lie outside the region of interest, i.e. outside the region stimulated by the relatively narrow (approximately 15° FWHM) HF pump beam.